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Potential for weather modification

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Cover:
Rainfall as a result of cloud seeding with dry ice - central Alberta, Canada, 28 August 1983.

ATMOSPHERIC SCIENCES DEPARTMENT, ALBERTA RESEARCH COUNCIL
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Foreword

Generally, the soil and climatic conditions in Alberta, Canada, are favorable for agriculture, which is one of the major industries in this western Canadian province. However, hailstorms and the lack of adequate moisture during the growing season often inflict severe crop losses.

Since 1956 there has been strong and continued support for weather modification research in Alberta, particularly from the agricultural community. Initially, most of the research was focused on hail suppression. In recent years, however, weather modification research has also been directed at rainfall and snowfall enhancement.

As a result of the recent research, it is now reasonable to seriously consider the potential of weather modification as a water management tool. This report summarizes the salient results of research on weather modification in Alberta, and discusses the possible role of weather modification in improving the agricultural industry.

Dr. R.G. Humphries, Head, Atmospheric Sciences Department, Alberta Research Council

Acknowledgments

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Abstract

Planned weather modification aims to offset detrimental effects of weather on human activities. It is generally considered to be a deliberate effort to improve atmospheric conditions for beneficial human purposes. Some weather modification efforts are to augment water supplies through enhanced precipitation; others, including measures to mitigate severe weather, are to prevent deaths and reduce crop losses and property damage due to hail. Results of weather modification experiments show that it must be considered as a possible future option in water management schemes.

Weather modification experiments are often compromised by the temporal and spatial variability in precipitation. This has led to weather modification assessments based on physical studies as part of exploratory programs.

Results of rainfall enhancement experiments in Alberta indicate that seeding small towering cumulus clouds with silver iodide (AgI) or dry ice (CO_2) produces results consistent with weather modification hypotheses. Repeated on many occasions, the experiments strongly suggest that cloud seeding can cause clouds to last longer and produce precipitation. Some experiments with hailstorms also produce consistent results; however, hailstorms remain insufficiently understood to develop sound hail suppression theories.

It is estimated that, in the growing season, precipitation in Alberta may be enhanced by at least ten percent using appropriate cloud seeding techniques. It must be emphasized that insufficient cases have been analyzed to claim statistical significance.

Since weather modification, at least rainfall enhancement, is a technology that cannot be overlooked in future water management strategies, it is important that attention be given to the complex interactions among social, economic, agricultural, and precipitation parameters.

Introduction

Planned weather modification aims to offset detrimental effects of weather on human activities. It is generally considered to be a deliberate effort to improve atmospheric conditions for beneficial human purposes. Some weather modification efforts are to augment water supplies through enhanced precipitation; others, including measures to mitigate severe weather, are to prevent deaths and reduce crop losses and property damage due to hail.

Industries such as agriculture, aviation, transportation, communications, energy (power generation), and construction are affected by weather. In particular, food and fiber industries are crippled by extremes in precipitation. Weather modification attempts are therefore particularly relevent in regions where extremes in water availability threaten human survival.

Considered as water management challenges, some options to planned weather modification are desalinization of water (for arid regions near large bodies of salt water or for geothermal brines), construction of wells, and transmountain or interbasin transfers of water. Other options, from an agricultural viewpoint, are the development of plant species having resistance to hail or to excesses and deficits of precipitation. An ambitious alternative is to arrange economies to have less dependence on precipitation, although this may result in undesirable social consequences. Weather modification has now developed such that is must be considered within the context of such available options.

This paper deals with weather modification as it pertains to agriculture. Results of weather modification experiments are reported and interpreted in terms of their repeatability and their relevance to agricultural engineering issues embracing hydrology, irrigation, and production on farms.

The experiences and results reported here are drawn mainly from experiments in Alberta, Canada. The Alberta Hail Project was established in 1956 and represents one of the longest continuing applied weather modification research programs in the world. Consideration is currently being given to the management of rainfall and snowfall, and to hail suppression. Central Alberta affords an ideal location for studying atmospheric effects and assessing their influence. Its mid-latitude continental location implies extremes in temperature. Positioned to the east of the Rocky Mountains, Alberta also commonly shows extremes in precipitation. The regional climatic regime is manifested in the development of extensive forests near the mountains, which give way to semiarid plains to the east. Major rivers derive water from melting snow and run eastward from the mountains through the plains.

Extreme rainfall events are common in Alberta. Figure 1 shows the long-term average of summer (July-August) precipitation in southern Alberta, along with the average precipitation for the five-year period 1974 to 1979, presented as a percentage deviation from the long-term average. Variations in precipitation are often two-to-one, in both north-south and east-west comparisons. Moreover, the deviation of the five-year average from the mean exceeds ± 20 percent for almost half the area shown. As a further illustration of the multiplicity of adverse weather events, figure 2 shows hailstorm tracks across the Alberta plains during the summer of 1983. More than 70 hailstorms are known to occur each year in the central portion of the province.

With a population of about two million people, Alberta has an agricultural industry with values of farm receipts amounting to about $4 billion (Canadian). Alberta produces about 25 percent of Canada's wheat and 50 percent of Canada's barley. This agricultural industry is critically dependent on the appropriate timing and amount of rainfall.

The relevance of weather modification in Alberta is summarized by the following:

- $100 million damage to crops and $25 million in property damage occurs each year due to hail.

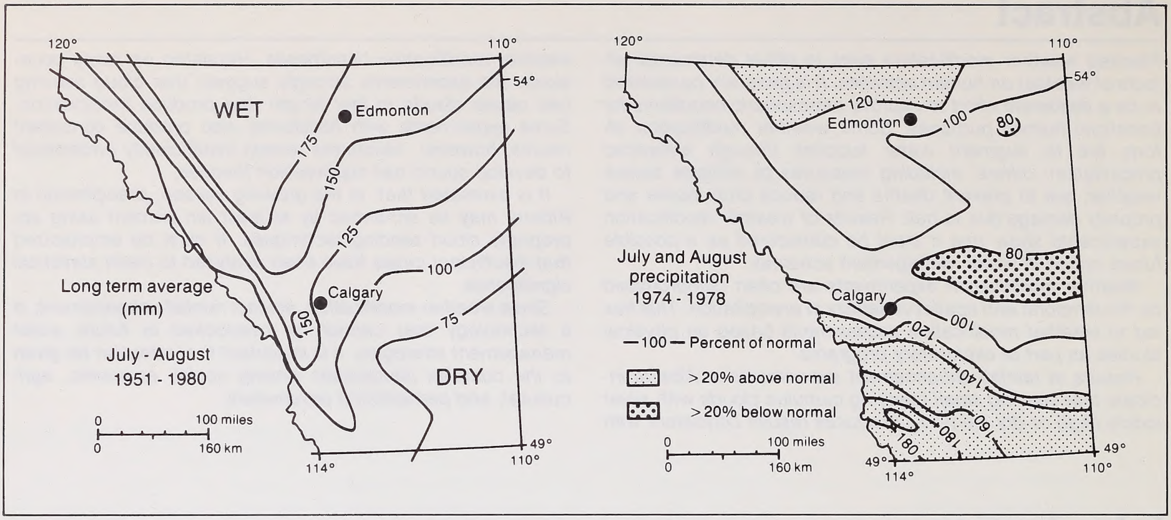

Figure 1. (left) Total precipitation (mm) in southern Alberta during July and August averaged over the period 1951-1980. (right) Percentage deviation from average total precipitation. Deviations calculated for the period 1974-1978.

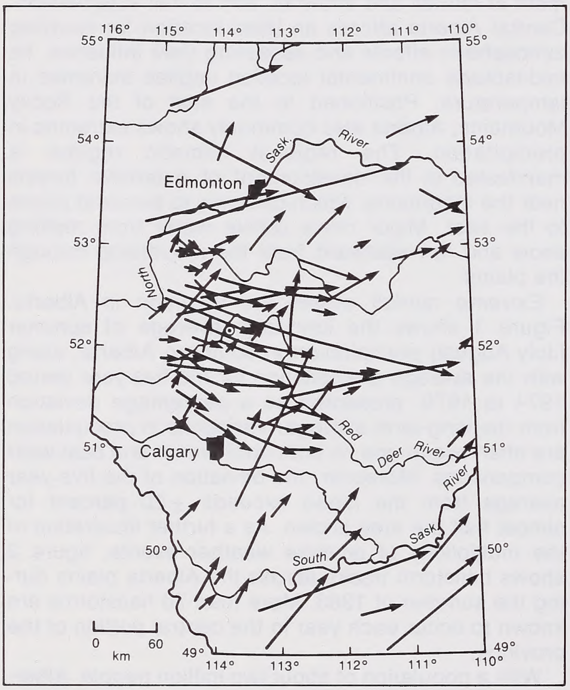

Figure 2. Hailstorm tracks in Alberta, 1983.

- Irrigation is a cornerstone for some farm producers in southern Alberta but stream flow to support irrigation activity is often marginal.
- Excesses of precipitation occur in regions accustomed to producing animal forage.
- Precipitation shortfalls limit cereal crop production.

These factors are characteristic of conditions that prevail in many agricultural economies of the world and have the potential to be solved through weather modification (Cleveland, 1979). As an example, precipitation enhancement through planned weather modification has the potential to offset the importance of transportation systems in water management schemes. If clouds can be made to rain or snow sufficiently, the precipitation so-produced supplements irrigation systems. River flow could be controlled by either increasing or decreasing the amount of precipitation produced over the river basin.

In addition to increasing water supplies, weather modification offers the potential for some relief from the variability in precipitation. However, it is the temporal and spatial variability in precipitation that is itself an inherent limitation in determining the efficacy of weather modification.

The potential for weather modification can only be assessed by well-planned experiments that meet the challenge to distinguish weather modification effects from widely varying natural precipitation events.

Variability in precipitation - the challenge in assessment of weather modification

Weather modification can be partly characterized as an attempt to alter the production of precipitation in space and time. Experiments are usually carried out by injecting (seeding) clouds with artificial agents such as dry ice (CO_2) or silver iodide (AgI), measuring the nature of the clouds and their precipitation after

seeding, and comparing them to similar clouds which are not seeded. The assessments can be conducted on a regional basis, or on a cloud-scale or local basis. Both kinds of assessment are complicated by the inherent variability in clouds and their consequent precipitation.

Regional assessments

There are many schemes (see for example Mielke, 1983) used to assess weather modification. Regional assessments are generally made by: a) comparing results of seeding events in a target area to conditions in a control area; or b) comparing the results of seeding events randomized with time over one area.

In the target-control experiments, it is important to compare regions where precipitation processes are similar and where seeding in the target area does not affect clouds in the control area. After, say 100, seeding experiments, the precipitation in the target area is compared to the precipitation in the control area. This scheme is severely compromised by the difficulty in selecting two regions where the natural precipitation regimes are similar, as illustrated by the regional variability in precipitation over Alberta (figure 1).

The temporal variability in precipitation also influences assessments in experiments which compare results from seeded and nonseeded conditions over one area. After a particular time period (five years for example), precipitation from days on which seeding occurred is compared to precipitation from days on which no seeding occurred. This experimental design is often compromised because the natural precipitation is highly variable over the course of the experiment, and seeding at one time (day) may affect precipitation at subsequent times (days). As an example of the variability, the average precipitation over a five-year summer period is shown in figure 1 as a percentage deviation from the long-term average (often greater than 20 percent). Moreover, in Alberta for example, the coefficients of variation[1] range from 0.2 for annual precipitation, to 0.5 for seasonal precipitation, to 1.0 for monthly precipitation. Although the variability is lower on a seasonal basis than on a monthly or daily basis, the time required for confirmatory experiments on a seasonal basis spans many years (Wong and Chidambaram, 1979). The primary implication of variability in precipitation is that it can easily mask useful modification effects for target-control experiments or for regional experiments where the seeding events are randomized with time. This is especially the case when modification effects, often projected to be about 10 percent in precipitation production, are small relative to the natural variability in space and time.

Variability in precipitation has limited the effectiveness of statistical evaluations, when aggravated by shortcomings in design, measurement methods, and numbers of test cases. This has now led to weather modification assessments based on physical studies as part of exploratory programs. The physical studies are usually conducted on a cloud-by-cloud basis, referred to as local assessments.

Local assessments

Weather modification experiments conducted on a cloud-by-cloud basis are subject to variability in the parameters which describe clouds. Both the selection of test clouds and the comparison of seeded and nonseeded clouds are compromised by measurement problems imposed by the variable precipitation.

In the selection of test clouds, it is desirable to have clouds which are alike prior to seeding. However, clouds are observed to vary widely in their physical parameters — size, liquid water content, ice crystal content, cloud base temperature, updrafts, and so on (see for example Dennis, 1980). In spite of this wide variation, large numbers of test clouds enable the measurements to be stratified into classes appropriate for comparison analyses. This ensures, to the greatest possible extent, that any differences detected after seeding are due to planned modification attempts and not due to inherent differences in the clouds themselves. In the selection process, in situ measurements are made with cloud physics research aircraft. The representativeness of these measurements is influenced by the variability of the physical parameters within the test clouds. As an example, broad-scale precipitation is characterized by low spatial and temporal gradients in liquid water content, whereas convective precipitation has high gradients.

The comparison of measurements from seeded test clouds and nonseeded test clouds is also influenced by the variability of physical parameters within the clouds. As in the selection of test clouds, the representativeness of measurements for comparison purposes made by aircraft flying through the clouds is critically dependent on the gradients of the physical parameters within the clouds. Comparisons of test clouds using surface-based observations are also subject to the effects of variability. For example, the use of surface-based observation networks appropriate for measuring synoptic scale precipitation will result in a large error (actual precipitation versus that measured by the network) for convective precipitation (Collier *et al.*, 1975). This is a consequence of the high spatial gradients in precipitation associated with convective storms.

Cloud-by-cloud assessments of weather modification have begun to reveal results that are consistent with weather modification hypotheses. This is a consequence of the relatively recent availability of high quality instruments used to measure physical parameters of clouds. However, not all of the factors associated with appropriate experimental design, test cloud selection techniques, and measurements have been fully resolved. Results in Alberta are from controlled cloud seeding experiments, with assessments based on data gathered from dense surface observational networks, weather radar, and cloud physics research aircraft. The cloud physics and weather radar facilities at the

[1]The coefficient of variation is the standard deviation in a set of observations, divided by the mean.

Alberta Hail Project are described by Humphries and Barge (1979) and Cheng *et al.* (1984).

The next section summarizes salient results associated with hail suppression, rainfall enhancement and feasibility studies of snowfall enhancement conducted during the past five years in Alberta.

Results of weather modification experiments in Alberta

Weather modification experiments in Alberta to date have been directed at rainfall enhancement and hailfall suppression. Limited investigations have also been conducted into the feasibility of seeding clouds positioned over the Rocky Mountains to enhance snowfall on the lee side of the mountains. The weather modification experiments are essentially conducted in three steps: 1) assessment of the nature (physics and dynamics) of the clouds to determine their suitability for seeding; 2) injection of freezing nuclei; and 3) monitoring the seeded test clouds to compare cloud precipitation parameters to those of nonseeded test clouds (Goyer and Renick, 1980).

Hail suppression

Background

Barge *et al.* (1984) and Krauss and English (1984) describe in detail how the space-time variability of hail, both within storms and at the ground, has been a limiting factor in the assessment of hail suppression efforts. They also discuss how hail suppression can be considered in small steps, through a number of sub-hypotheses in the framework of an overall hail suppression hypothesis. The basic physical hypothesis underlying the present Alberta technique for hail suppression is that large damaging hailstones occur because of a natural deficiency of freezing nuclei. In the seeding hypothesis, it is assumed that a chain of physical processes leads to more and earlier embryo (graupel, or small hail) production, starting with an increased concentration of ice crystals. It is suggested that the injection of suitable numbers of additional nuclei promotes the formation of many smaller, less damaging hailstones. Experiments have been conducted for three years (1982-1985) to test the sub-hypotheses that seeding results in an increased concentration of ice crystals and that some of these ice crystals grow sufficiently to become hail embryos.

The basic conceptual model of the precipitation processes rests on the assumption that the dominant hail formation mechanism involves graupel particles which are grown within feeder clouds and then transported by the wind into the main storm where they grow to hailstones along the edge of the main updraft. The term "feeder cloud" is used for a convective cloud turret located upwind from the main storm with respect to the low level and midlevel flow.

Experimental procedures

The physical experiments, which are conducted on a cloud-by-cloud basis, involve feeder clouds which are selected, seeded, and monitored, using a seeding aircraft and a sophisticated cloud physics research aircraft. Clouds are considered to be suitable test clouds if certain criteria are met: supercooled liquid water content exceeds 0.5 $g.m^{-3}$ and ice crystal concentrations are less than 1 L^{-1} with all measurements taken over a 500 metre distance. Once a cloud has been selected for treatment, either silver iodide or dry ice is injected into the cloud by the seeding aircraft. After treatment, systematic penetrations of the test cloud are conducted with the research aircraft to document the effects of the treatment (Atmospheric Sciences Department, 1984).

The physical experiments conducted on hailstorms in Alberta comprise randomly selected treatments applied to the tops of feeder clouds and include seeding with droppable AgI flares, seeding with a low rate of dry-ice pellets, seeding with a high rate of dry-ice pellets, or treating with a placebo. Accordingly, the seeded cloud represented in figure 3 was seeded with a high rate of dry-ice pellets, that is, approximately 100 g of dry ice every 100 m for a total of about 1280 g of dry ice.

Discussion of results

Results from in-cloud measurements of one seeded and one nonseeded feeder cloud of the hailstorm that occurred on 26 July 1983 are shown in figure 3 (Krauss and English, 1985). Although the cloud widths and initial liquid water concentrations of the two test feeder clouds were similar, the evolution of the microphysical processes was quite different (figure 3). The average ice concentration was greater for the seeded cloud at all times up to 21 minutes after treatment. An ice plume concentration of 1490 L^{-1} was observed 2.5 minutes after seeding with dry ice. The greater ice concentrations in the seeded cloud depleted the liquid water faster than in the nonseeded cloud. Precipitation developed earlier in the seeded cloud than in the nonseeded cloud. In fact, radar observations show that the feeder cloud treated with a placebo (nonseeded cloud) developed an echo 16 minutes after treatment at the -20 degree level and went on to develop into a mature cell with radar reflectivities greater than 55 dBZ (hail likely). The seeded feeder cloud developed a radar echo 7 minutes after seeding at the -12 degree level and reached a maximum reflectivity of only 43 dBZ (hail unlikely).

Figure 3 also shows that the cloud seeded with dry ice produced a high concentration of riming size particles and produced more 2 mm precipitation particles more rapidly than did the cloud that was treated with a placebo. Similar experiments have been repeated on other occasions (Krauss and English, 1985) and lend support to the hypotheses that seeding increases the

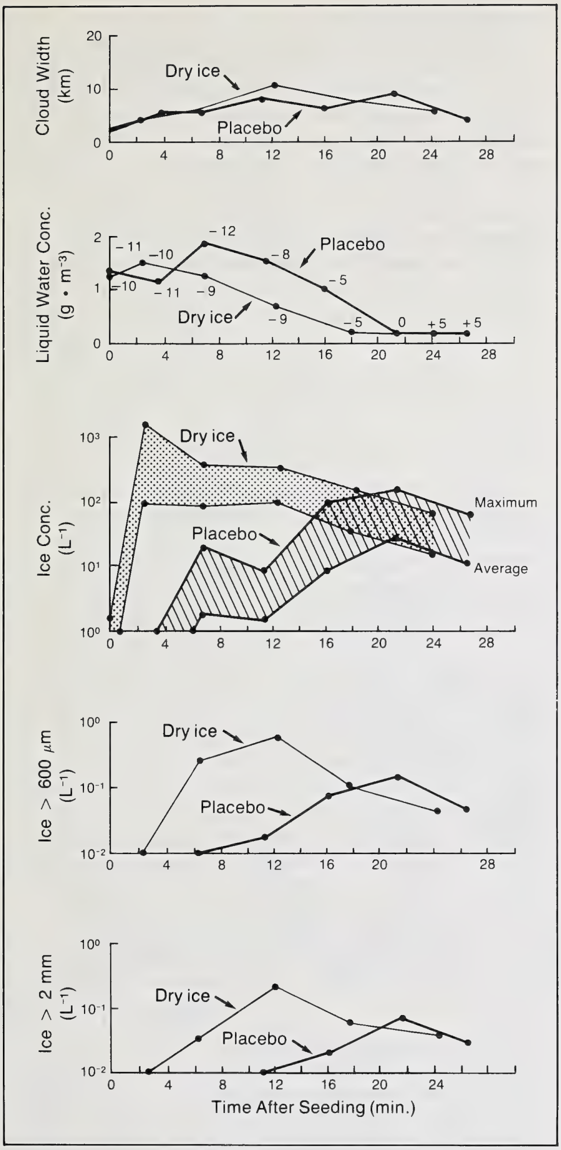

Figure 3. Microphysical observations from seeding trials conducted on 26 July 1983. Each data point represents a cloud penetration by the research aircraft. On the liquid water content diagram, the temperature at each penetration is in °C.

ice crystal concentrations, which in turn leads to the earlier production of increased quantities of smaller hail. It remains to be resolved whether the increased production of smaller hail results in fewer large damaging hailstones, as predicted from the overall cloud seeding hypothesis.

Hailstones have been observed at the ground from both seeded and nonseeded storms. These observations are summarized by Cheng *et al.* (1985). Their observations and analyses center on hailstone distributions with size, well understood to be given by $N(D)dD = N_0e^{-bD}dD$, where D is the hailstone diameter (5 mm < D < 5 cm), N(D) is the hailstone concentration, b is a slope parameter and N_0 is the concentration of 5 mm hailstones, as shown by Douglas (1964). The Cheng analyses go on to show that there is a relationship between N_0 and b that is extremely relevant, even before comparing hailstone size distributions for seeded and nonseeded storms. For example, the relation between N_0 and b implies that as the number of smaller hailstones increases, as predicted by the hypotheses discussed above, the slope in the exponential size distribution also increases; consequently, with sufficient increases in the numbers of small hailstones, there will be decreases in the maximum size of stones, provided that the moisture available to a hailstorm remains constant. Recent stratification of the same hailstone samples by Cheng and English (private communication) indicates that the total concentration of hailstones N(D) is larger for seeded storms than for nonseeded storms, based on analyses of 106 hailstones sampled at the ground from 10 storms.

The increased concentration of hailstones at the ground from seeded hailstorms versus nonseeded hailstorms is consistent with the increased ice crystal concentrations observed following cloud seeding. Although this consistency in observations appears promising, a cause-effect relation has not yet been established, because no appropriate test clouds have been seeded, observed by aircraft, and then measured by ground systems to provide a complete test case.

Rainfall enhancement

Background

Extensive controlled cloud seeding experiments have been conducted in Alberta since 1978 (see, for example, English and Marwitz, 1981). Recent experiments are discussed primarily by English and Kochtubajda (1984), Kochtubajda and Rogers (1984) and Kochtubajda (1985). The experiments to increase rain rest upon the hypothesis that the ice process can be initiated early by introducing ice nucleating material into clouds. Initiating the ice process early implies initiating the growth of ice crystals by accretion of supercooled water droplets (a process that occurs rapidly within clouds) before the ice crystals and water droplets evaporate when dry air is entrained into the clouds.

Experimental procedures

The experiments are conducted in a fashion similar to the hail suppression experiments described above. Using the seeding aircraft and cloud physics research aircraft, clouds are selected and seeded. Clouds are accepted for experiments if the liquid water contents are in excess of 0.5 $g.m^{-3}$ and ice crystal concentrations are less than 1 L^{-1} for 5 consecutive seconds of observation from the research aircraft at -10°C within the cloud. In addition, the cloud top temperature must lie within a range of -7°C to -15°C and the cloud width must be less than 10 km. An updraft must be present

for a cloud to be accepted, and there must be no echo detectable on the aircraft radar. Once selected, the treatments of the clouds are randomized. Three treatments are possible: 1) seeding with dry ice pellets; 2) seeding with silver iodide pyrotechnic flares; and 3) treating with a placebo. As part of the experiments, clouds are grouped into sets of three, taking into account that on a given day, experimental clouds would be similar so that any differences in the response to the treatments could be ascribed to the treatments themselves.

Once the clouds are seeded, the research aircraft penetrates the test clouds repeatedly, while they are photographed from the seeding aircraft. In addition, the experimental clouds are observed by the precise S-band and C-band radars.

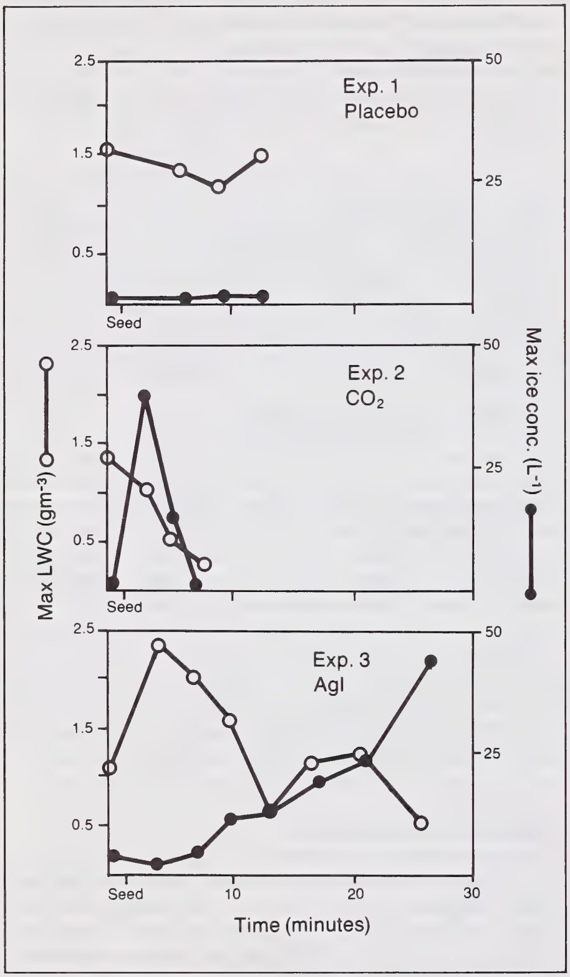

Figure 4. Results of three seeding experiments conducted on 21 June 1983. The maximum liquid water content and ice crystal concentrations are shown for each cloud penetration (represented by dots) by the research aircraft.

Discussion of results

To date, 80 clouds have been treated as part of the rainfall experiments and 39 have been analyzed in detail. The results show a high degree of repeatability in the production of ice crystals in clouds seeded with either silver iodide or dry ice, as compared to those treated with a placebo (nonseeded). As an illustration, results of seeding trials conducted on 21 June 1983 are shown in figure 4. In the cloud treated with a placebo, ice crystal concentrations remain very low even 10 minutes after treatment. For clouds seeded

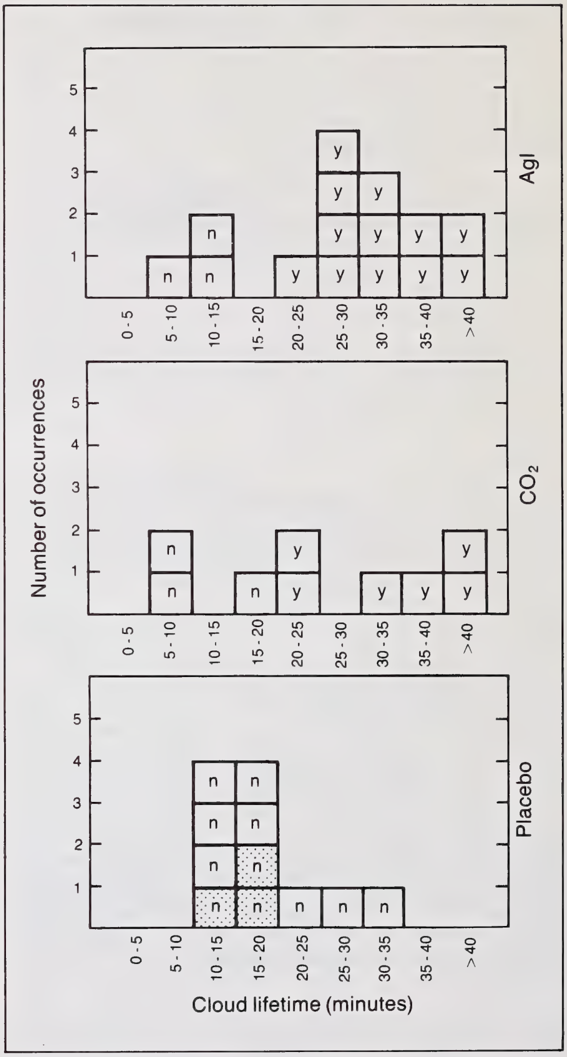

Figure 5. A frequency distribution of 35 test clouds, grouped by the treatment applied, stratified according to cloud lifetime and classified on a yes (y)/no (n) basis with respect to precipitation initiation. The stippled areas represent experiments which terminated early for which the cloud lifetime is underestimated.

with silver iodide and dry ice, ice crystal concentrations rise rapidly after seeding, and the liquid water content decreases with time. The increase in ice crystal concentration and decrease in liquid water content is consistent with the hypothesis that the ice crystal process is initiated, and that ice crystals are growing, through the accretion of supercooled liquid water.

The repeatability of these results is illustrated in figure 5. For each cloud seeding treatment, the distribution of yes/no indications of precipitation initiation with cloud lifetime is shown. The yes/no indication of precipitation is based upon the production of radar echos by the experimental clouds. In a few cases where radar data are not available, the notes of scientists aboard the research aircraft were used to determine whether or not precipitation was visually observed to fall from the clouds. Figure 5 shows that if the test clouds last 20 minutes or longer, precipitation tends to be associated with clouds seeded with AgI or CO_2. Clouds treated with the placebo tend not to produce rain, regardless of their lifetime. The information in figure 5 also implies that treating the test clouds with silver iodide or dry ice tends to extend the cloud lifetime. This is based on the observation that most of the placebo-treated clouds lasted less than 20 minutes.

The fact that the above cloud physics experiments have been repeated on numerous occasions indicates that the ice crystal process can be initiated by seeding cumulus clouds and that the clouds seeded with silver iodide and dry ice tend to last longer and produce precipitation. These observations suggest that cloud seeding may help to make rain and therefore have the potential to enhance areal rainfall.

During the cloud seeding experiments, some clouds were seeded with more seeding material than the amount specified for the rainfall enhancement experiments. In such cases, test clouds turned into clouds composed entirely of ice crystals that soon evaporated, producing no precipitation whatsoever. These observations suggest that overseeding cumulus clouds has the potential to inhibit rainfall. In combination with the rainfall enhancement experiments, this suggests a potential for overall rainfall management.

Snowfall enhancement

The principles associated with snowfall enhancement in mountain areas have been described in detail by Hill (1984) and Grant and Kahan (1974). The physical processes involved relate to transforming available liquid water within snow clouds to ice crystals of sufficient size to fall to the surface. Experiments on snowfall enhancement have not yet been conducted in Alberta. However, the first in situ observation of snow clouds over the Rocky Mountains of western Canada indicate the existence of cloud liquid water which could be transformed into ice crystals to enhance snowfall. These observations are considered sufficient evidence for a future experimental program.

The most significant results related to snowfall enhancement have been obtained in the United States. Experimental seeding of winter orographic clouds has shown increases in precipitation of 10 to 20 percent in some of the western states, provided that the seeding can be limited to clouds having certain well-defined characteristics (Super and Heimbach, 1983).

Comparison of results on a global basis

Hail suppression

In addition to the investigations described in the preceding sections, in-depth studies of hailstorm phenomena have also been conducted in the United States, Switzerland, and the Soviet Union. Soviet scientists are the most optimistic regarding hail suppression (Abshaev *et al.,* 1984a, 1984b). Often reporting perfect success, they indicate a cost benefit ratio of 1:4.

An effort to duplicate this Soviet technique was undertaken in Switzerland. In contrast to the Soviet reports, results of these investigations were not encouraging (Federer *et al.* 1984). Several questions were raised: Had the seeding been executed according to the Soviet prescriptions? Would a stratification of hailstorms permit discrimination of positive and negative effects? and Were there any significant effects whatsoever?

Extensive hail research projects in the United States (NHRE in particular) suggested that hailfall may be either increased or decreased by cloud seeding (Knight *et al.,* 1979).

A common theme which prevails in the literature is that hailstorms are insufficiently understood for development of a fully justifiable hail suppression theory. Understanding the variability of cloud physics, kinematics, and dynamic parameters in space and time is particularly important for future hail suppression research.

Rainfall enhancement

Results of other experiments in Canada (Isaac *et al.,* 1982), the United States (Cooper and Lawson, 1984), and Israel (Gagin, 1981 and Gagin and Newmann, 1981) are consistent with the rainfall enhancement results presented above. Schemenauer and Isaac (1984) indicate that cloud seeding to enhance rainfall is closely connected to cloud lifetime. Moreover, Hobbs and Politovich (1980) observed significant changes in the microphysics of clouds following seeding with either silver iodide or carbon dioxide.

Results in perspective

There is reason for qualified optimism regarding rainfall and snowfall enhancement. This viewpoint is also expressed by Walkinshaw (1985), based on a study commissioned by the United States National Oceanographic and Atmospheric Administration (NOAA) that projects that confirmatory experiments for snowfall enhancement, rainfall enhancement, and hail suppression would require 13, 16 and greater than 20 years, respectively.

Estimates of rainfall enhancement by weather modification

The results of weather modification experiments can be used by agricultural engineers and water management specialists. In particular, by using results from Alberta, this section illustrates techniques for arriving at estimates of local rainfall enhancement.

Figure 6 shows the path of a cloud seeded with CO_2. The path is represented by the positions of radar echos with time. Note that seeding was conducted at 1823h; shortly afterwards, at 1829h, a radar echo occurred, signalling the initiation of precipitation within the cloud. Without accounting for evaporation, the average rainfall rates can be derived from radar echos of the test clouds using a technique similar to that described by Barge *et al.* (1979). These rates range from less than 1 mm h^{-1} up to 5 mm h^{-1} over the cloud lifetime. The total rain that fell from the cloud was 97 000 m^3 as the cloud traveled 16 km due east.

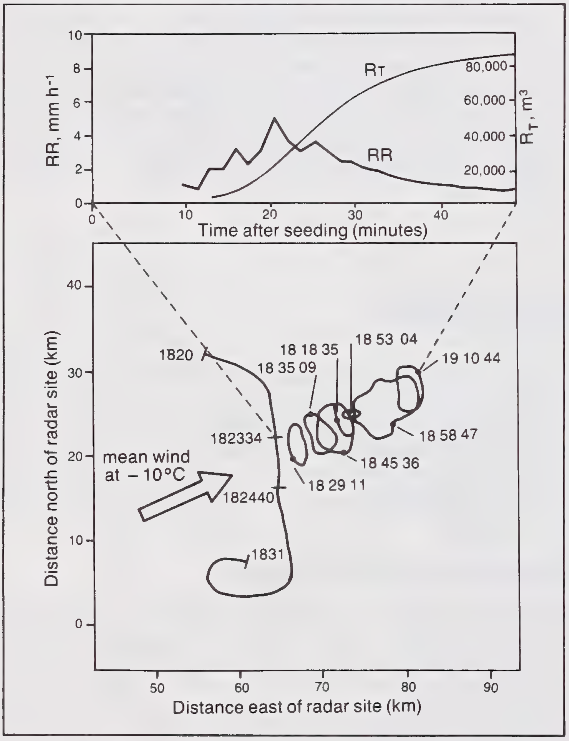

Figure 6. (lower) Outlines of a test cloud determined from radar data, together with the flight track of a seeding aircraft. Seeding occurred between 1823:34 and 1824:40 h (interval between tick marks on the flight track). (upper) The mean rainfall rate RR (mm h^{-1}) and the cumulative (total) rainfall R_T (m^3) are shown as a function of time after seeding.

The total rainfall for 10 test clouds (one of which is represented in figure 6), is shown in figure 7 as a function of cloud lifetimes. Clouds treated with placebos lasted less than 20 minutes and did not produce rain. In contrast, clouds seeded with dry ice lasted from 25 minutes to 80 minutes and produced between 0.1 mm and 1.6 mm of rain.

The information in figure 7 is assumed to be representative of the precipitation that may be induced by cloud seeding. Note that we are not asserting that seeding produced the rainfall, because sufficient cases have not yet been developed; however, the physical observations to date suggest that rainfall was induced. Moreover, the rainfall amounts are specific to the test clouds that were selected using specific criteria outlined in previous sections. Current experiments have been extended to test clouds which are more vigorous (cloud tops are colder, cloud widths are greater, and so on). We anticipate that the more vigorous clouds will last longer and produce more rainfall; however, we cannot speculate on whether or not additional precipitation can be derived from the more vigorous clouds by seeding.

Figure 8 shows estimates of seasonal rainfall enhancement on the ground resulting from cloud seeding. From figure 6, a typical seeded cloud is assumed to produce 0.5 mm of rainfall. Within the summer growing season in Alberta, there are estimated to be between 40 and 250 occasions when clouds suitable for potential rainfall enhancement occur. Assuming clouds on each occasion to be seeded in the same manner that test clouds were seeded, figure 8 shows that total rainfall enhancement can easily exceed 10 mm (see dashed line on figure 8). In seasons when there are many (say 250) occasions for rainfall enhancement, 25 mm of excess rainfall could be produced with only a 0.2 probability of clouds passing over a ground location. In seasons with fewer (40) occasions, 10 mm of excess rainfall could be produced with a 0.5 probability of clouds passing a ground location. It should be noted that on any rainfall enhancement occasion, more than one cloud may pass over a ground location.

These results show the need to connect results of weather modification to climatological conditions. They represent a reasonable approach for using available weather modification results of the type now being obtained in Alberta. Only when (and if) the results are shown to be significant should this approach be applied to practical weather management problems.

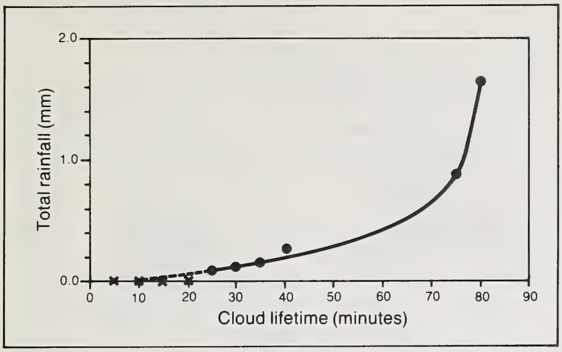

Figure 7. Total rainfall (mm) from six clouds seeded with CO_2 or AgI (dots) and four clouds seeded with placebos (x's) averaged over cloud area and lifetime, shown as a function of cloud lifetime.

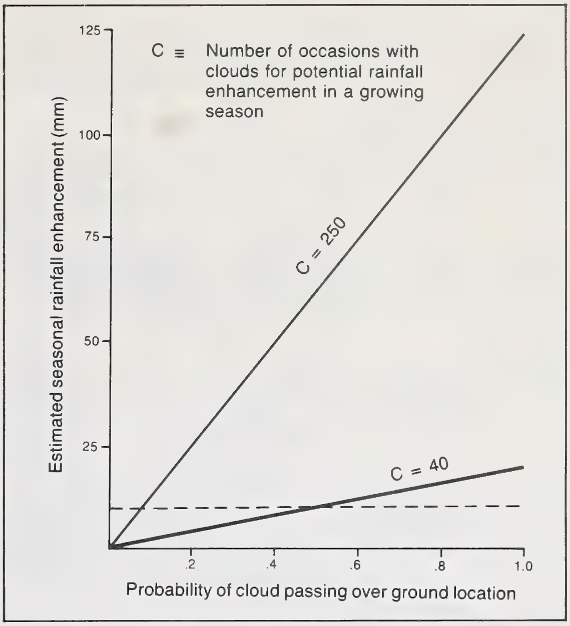

Figure 8. Estimates of total seasonal rainfall enhancement as a function of the probability of a cloud passing over a ground location. Estimates assume a range of 40 to 250 occasions with clouds for potential rainfall enhancement in a growing season.

Weather modification and water management for agriculture

A coordinated approach to water management that encompasses snowfall and rainfall management is particularly appropriate. Using southern Alberta as an example, figure 9 is a schematic illustration of water resources and their availability to agriculturalists. Note in this diagram that the water available for irrigation purposes has two sources: 1) snowmelt originating in the mountains, and 2) runoff associated with summer rainstorms. Other water available for agriculture, whether in irrigable areas or not, comes directly from soil water storage resulting from winter snowmelt and summer rainfall. This combination of available water from both local and remote sources must be optimized for various uses, particularly agriculture.

Weather modification, as reported in earlier sections, has the potential to influence both the local and remote source water. In effect, the challenge is to maximize water availability using a combination of techniques, including weather modification, irrigation reservoir development, irrigation transfers and other water transport possibilities. Ensuring optimum water availability implies comparing these techniques using criteria such as the probability of achieving the desired results, the time to implement, and the cost.

These comparisons require detailed assessment of information on weather modification, agricultural production, economics, and social issues, which vary from time to time and region to region. In weather modification, factors which must be accounted for in consideration of snowfall enhancement are that: a) effects are likely to be maximized in mountain regions, b) effects are cumulative during winter periods when there is no melting and any losses of water content are due to sublimation, and c) snowfall enhancement may influence dam and reservoir management. Rainfall management may influence runoff, resulting in similar downslope effects on dams and reservoirs. In addition, local weather modification activities can affect the performance of irrigation systems and the growth of various crops (through, for example, increased rainfall potentially causing reduced evapotranspiration).

Successful planned weather modification can influence the development of alternate water storage and transport systems, crop rotation techniques, and use of new crop species. As a consequence, new water management schemes imply alterations of economic patterns that may, in turn, affect social traditions. These complex interactions among social, economic, agricultural, and precipitation conditions suggest that intensive efforts must be mounted to quantitatively assess the interactions. Advancements in economic models, crop production models, and transportation systems, as well as interactions among these systems and water management, are likely to be well understood by the time any practical weather modification technology emerges in future decades.

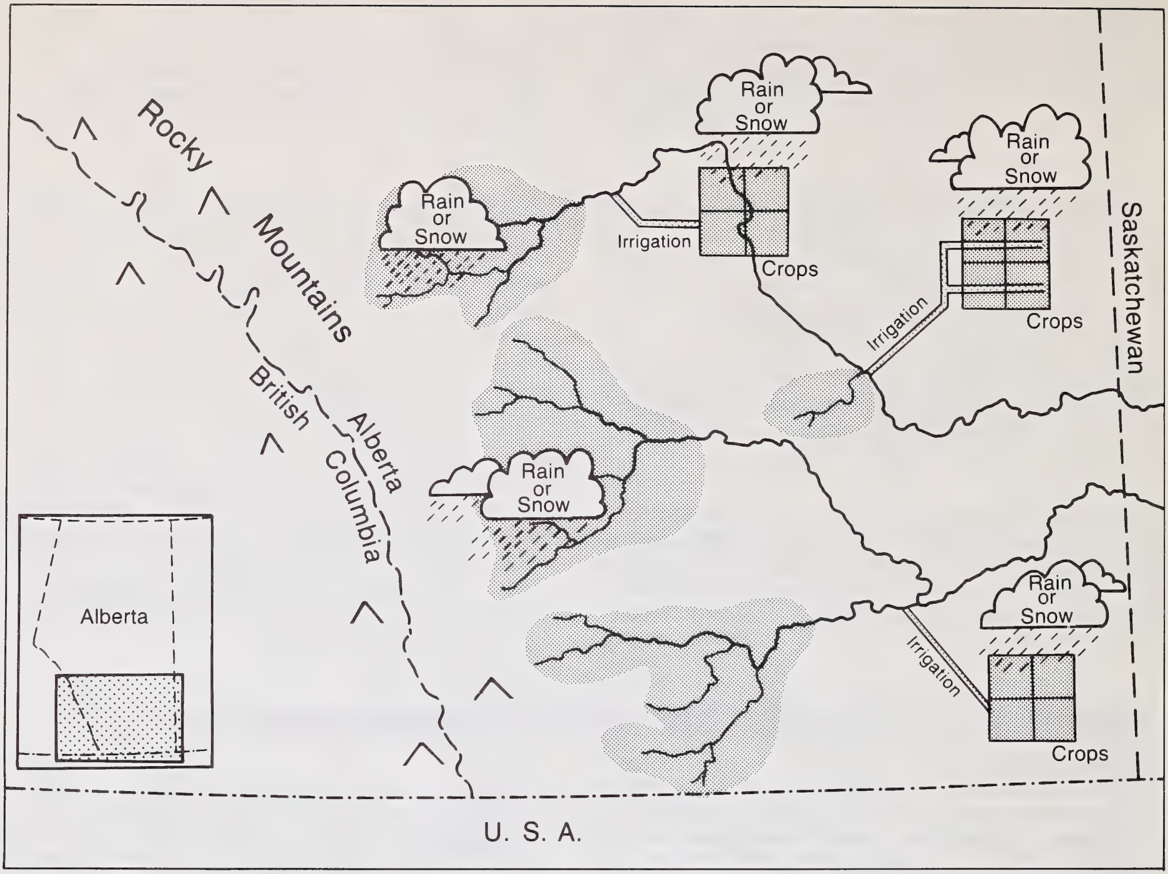

Figure 9. Schematic representation of water resources and their availability to agriculturalists in southern Alberta. River basins and crops are shaded.

Summary

Weather modification is not a proven technology but has potential for application within one or two decades, given appropriate attention to technical assessments, model development, observations, technology development, and improved water management systems. Planned weather modification is a technology that cannot be overlooked in the development of future water management strategies. As indicated by Cleveland (1979): *The key conclusion in this report is that a useable technology for significantly enhancing rain ... is scientifically possible and within sight.*

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